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Nondestructive Evaluation of Heavy Section Pressure Vessels

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Dr. N.F. Eaton
Director General

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NONDESTRUCTIVE EVALUATION OF HEAVY SECTION PRESSURE VESSELS

Contract Serial No. OSQ79-000-78

1. Introduction

The Welding Institute of Canada was approached by CANMET-Energy, Mines and Resources - Physical Metallurgy Research Laboratories to carry out research on ultrasonic inspection of thick wall pressure vessels. This work is part of a large program developed by CANMET-PMRL. Its objective is the upgrading of Canadian capabilities in the manufacture of thick wall pressure vessels, especially for use in the petrochemical processing industry. A survey of the literature on the subject was issued as a separate report.

Phase I of the project, described in this report, led to (the conceptual) designing of an automated inspection system capable of scanning pressure vessels of up to six inch wall thickness without cladding.

The work carried out included the preparation of a weld sample containing artificial defects, characterization of the UT properties

of the weld metal, ultrasonic contact and immersion scanning, and a conceptual design of the system.

2. Problem Definition

Ultrasonic testing (UT) is the only viable method for reliable inspection of thick wall pressure vessels. Even with proper orientation, X-ray or γ-radiography (RT) can detect no more than very gross flaws.

There are some problems, however, inherent in the ultrasonic testing of thick vessels which are not encountered in a thinner wall inspection. These include:

- high UT attenuation along the long path of the sonic beam
- need to use lower frequencies which limit the resolution
- long travel times of the UT beam which make the timing and gating of the signals critical
- need to use many transducers to cover the whole volume of the weld
- need for proper multiplexing of the transducer signals
- complex display of data coming from many channels (transducers).

The approach taken was to use a prepared sample with artificial defects, in order to study the interaction of the UT beam within the sample with the flaws and to define inspection techniques.

3. Sample Preparation

A slab of steel approximately 23" long x 7" wide x 6" thick was obtained from CANMET-PMRL for the program. A double 'V' joint had been prepared with angles at $22\frac{1}{2}^{o}$ to normal along the length of the section.

Two sections were sawed from the slab to result in a specimen size of approximately 13" long x 5" wide x 6" thick with a double 45^{o} V welded position.

(a) Artificial Defects Introduction

Two grooves and three flat bottom holes ¼" deep with varying diameters were machined in one 'V' face (Figure 1). The defects were filled with ceramic paste and thoroughly dried before the welding operations.

The grooves would simulate the lack of side wall fusion defects and the flat bottom holes the cracking in the heat-affected zone. The positions of all flaws were recorded for future ultrasonic work.

(b) Welding of the Specimen

5/8" thick run on, run off tabs were stick welded to the sides of the 'V' joints in preparation for submerged arc welding. Handles were also welded to the ends of the specimen for ease of handling during the welding and testing operations.

The root pass was SMA welded manually with an E7018 (1/8" diameter) electrode. A Hobart Welder was used with settings of 150 amps and 23 volts. Because of the extremely narrow root region, seven passes on side one (the side containing the artificial slots) and 5 passes on side two were manually welded with the above settings. It should be noted that prior to welding and during the welding operations the specimen was preheated to 350^{o}F and held at this temperature by the use of an oxy-acytelene torch. Checking of the temperature was done with tempil sticks.

The remaining portion of the joint was submerged arc welded with an Esab LAD 1000 machine. L61 (1/8" diameter) wire was used with Linde 709-5 flux. The settings varied slightly during the welding of different passes. An average of 600 amps, 32 volts and a travel speed of 15 ins/min was used.

A total of 77 passes were run on side 1 and a total of 84 passes on side 2.

After completion of the welding, the run off tabs were machined off and a ½" thick section was cut to preserve a macrosection of the weld (Figure 2). Excessive bead build-up was milled from top and bottom.

Three 1/8" diameter reference holes were drilled in the specimen (Figure 3).

The specimen was then painted to minimize corrosion during immersion testing. Figure 4 shows the completed specimen ready for UT inspection.

(c) Radiography

γ-radiography was carried out externally by Quantum NDT. The Co-60 γ-source of 100 Ci intensity was used. The source film distance of 90 cm and film type Kodak AA resulted in a film density of about D ≈ 2.5 after the exposure of 65 min.

A print radiograph of the weld is shown in Figure 5. The defects introduced prior to welding are not revealed; only the flat bottom

hole ϕ 0.25" is showing marginally. The 0.25" diameter hole results in a change in thickness of ~4.1%. The above exercise demonstrates the severe limitations of radiography for thick wall inspection. The orientation dependence of flaw detectability combined with the low penetrameter sensitivities make radiography grossly inferior to the ultrasonic inspection (especially for planar flaws).

4. Ultrasonic Measurements on the Pressure Vessel $2\frac{1}{4}$ Cr/Mo Material

The intended material for thick wall pressure vessels is Japanese pressure vessel steel (2.25 Cr/Mo) rolled into a six inch thick plate. A sample provided by CANMET-PMRL was used to determine the ultrasonic velocities and their temperature dependence, and to obtain some data on UT attenuation. The UT sample geometry is shown in Figure 6 and the block diagram of the set-up is shown in Figure 7. The velocity was determined using a 2.25 to 7.5 MHz transducer and H-P 5300 series time counter. The limited temperature dependence of UT velocity was also determined.

The ultrasonic velocity is anisotropic due to the textures introduced by rolling in the plate. The longitudinal velocities in the X, Y, Z directions were as follows:

v_x = 5850 m/s $\qquad$ v_y = 5800 m/s $\qquad$ v_z = 5780 m/s

The anisotrophy in velocities is over 1%.

The temperature dependence of UT velocity was established between 5° and 45°C to give the slope of the velocity vs. temperature curves. The measurements are plotted in Figure 8. The velocity drops with temperature about 1% per 40°C, but the slope is uniform for different orientations.

The attenuation in the samples was found to be a moderate 8.610^{-2} dB/mm at 4 MHz. The attenuation of the signal will not cause any difficulties during the UT inspection.

5. Weld Coverage by the Ultrasonic Beam

The ultrasonic beam should impinge on the defects at normal incidence. Since orientation of defects varies over a wide range of angles, the arrangement of transducers should match the orientation of flaws.

Figure 9 shows the coverage achieved by seven transducers. The refracted angles from normal to up to seventy degrees are used to cover all orientations of possible flaws in the weld region.

Table I lists the parameters of the seven transducers, e.g., the refracted angle, entry point from weld axis, longest beam path, corresponding travel times and expected defect type to be revealed by a given transducer. The other side of the weld is covered by a mirror arrangement of the transducer head. The distances in the weld correspond to

longest travel time of ∿ 80 μs (see Table 1). The table shows how different regions have to be separated by time gating.

6. Possible Defects in Weld Region

The possible defects are listed in Table 1. Most critical will be the lack of interpass fusion, lack of side wall fusion, and the cracking in the root region. Smaller defects like slag inclusions are not importnat, considering their effect on structural integrity. The intended ultrasonic method will also allow for some sizing of the flaw.

Artificial defects were introduced to simulate the possible flaws (see Table 1 and Figure 3).

All the artificial flaws were successfully detected. Each flaw type required an individually set transducer. Experiments showed that defect sizes defined by relevant ASME code will not be difficult to resolve.

7. Ultrasonic Testing

(a) Contact Testing

A contact testing using the Branson-Sonoray 600 UT flaw detector was carried out at a frequency of 2.25 MHz. Normal incidence as well as refracted angles of 45^{o} to 70^{o} were used. Since the Sonoray flaw detector has high gain (∿ 90 dB) signals received

were strong and clear, and also noise free. The lateral resolution of the scanning, however, was relatively poor due to the large divergence of the ultrasonic beam from the small 0.5" diameter transducers.

Figure 9 shows how the defects introduced to the weld were picked up. The sensitivity setting was carried out on 1/8" side drilled holes (D), (E) in Figure 3. Also, the normal flat bottom hole (F) was no challenge to a properly set UT tester. The technique, however, produced no permanent record. The screen signals were clear and strong (see Figure 10) with high signal to noise (S/N) ratios. The need for a permanent record led to the introduction of immersion testing.

(b) Immersion Testing

The immersion testing was carried out in a tank ∿ 24" x 18" x 10", deep, equipped with a precise scanner. The stepping motor-driven scanner allowed for X steps of 0.065 mm (0.0026") and Y steps of ∿ 0.001". The block diagram of the system is shown in Figure 11. An example of the modified C-scan display showing 3 artificial defects can be seen in Figure 12. The size of the reflectors can be estimated using a 6 dB drop method. The signal levels of the 2.25 MHz transducer were low at the back wall of the piece. The timing and transducer spacing are also of importance, since the back wall signal should arrive before the second front wall reflections. For this reason, a special type of transducer was purchased. The problems related to the choice of the transducer are outlined in Section 8.

7. Conceptual Design of the UT Inspection System

The experimental work carried out in this project combined with the literature survey led to a conceptual design which is detailed below.

The automated ultrasonics can be characterized by several key factors, namely:

- multitransducer arrangement to cover the whole volume of the weld
- immersion coupling with possible combination with gap testing
- low frequency of transducer, e.g., below 5 MHz
- focussed transducers in combination with the non-focussed ones
- stable mechanical scanning system driven by stepping motors
- multipulser arrangement combined with electronic multiplexing and analog switching of the signals
- complex gating of the signal to allow for "sandwiching" of the whole thickness of the weld
- both analog and digital signal processing to suit the application
- permanent data storage on the recorder charts or on magnetic discs
- preset scanning parameters combined with the manual over-ride control.

The required coverage of the weld depends on the welding method. The geometry of the submerged arc weld in the test piece will differ from other kinds of welding, such as narrow gap, or electroslag welding. The arrangement of the transducers must be made to ensure the coverage of the whole weld volume.

Proposed System

The proposed system is based on the Z-80 microcomputer. Figure 16 shows the block diagram. The central part is the Z-80 CPU which provides the control signals to the multiplexers, UT pulsers, and peripherals.

The system uses:

- eight individual pulsers
- eight gates, one for each channel, adjustable in width and delay
- common RF amplifier
- peak detector
- A-D converters for the interface with the computer
- mechanical scanning drivers
- D-A converter for the X-Y recorder
- printer
- CRT control console
- dual floppy disk drive for data storage

The system will be versatile enough to allow for the setting of a number of transducers and different weld geometries.

The block diagram of the proposed system is shown in Figure 16. The control microcomputer is Z-80 based. Programming will be done mostly in machine language (assembler) to cut the CPU time per operation.

The microcomputer will have two tasks; firstly, it will control the mechanical scanning via signals to stepping motor drives, and secondly, it will be used for data acquisition and data processing. The analog to digital converter and analog switching or multiplexing will be used.

Although the data acquisition is relatively straightforward, data processing and display can be very complex. Given the scale of the project data acquisition will be emphasized over data processing and display.

8. Choice of Transducer

Thick wall inspection is dependant on the properties of a transducer. Parameters like frequency, beam spread, near field length and damping are crucial since they determine the resolution and sensitivity of the system. The sensitivity is especially great in the oblique incidence transducer. For high refracted angle 60-70^{o} the return beam path in steel can be as much as 90 cm (see Table I). Such a distance will lead to a considerable beam attenuation and beam spread. The signal levels from a small defect may then be comparable with noise figures. The region around the weld root is critical. Several methods are available to overcome the difficulties, viz:

- using highly focussed beam transducer with long focal length
- using double probes with inclined beams (de Sterke probes)
- using signal averaging.

For wall thicknesses considered in this project, e.g., up to 150 mm, a highly focussed large diameter transducer is proposed for the root region (see Figure 13). This immersion type transducer developed by CEA Centre at Saclay is now commercially available. The transducers of this type are characterized by large focal length and small foci. The signal to noise ratio and sensitivity are excellent. In addition, the depth of focus is considerable (see Figure 14 and 15).

This type of transducer will be advantageous for the inspection of the root region, e.g. the far surface. For defects close to the near surface, simple (less expensive) transducers will suffice.

The immersion type of coupling can be made local to simplify the testing. Such a solution is proposed for a thick wall inspection system.

It is possible to combine gap coupling with local immersion coupling, depending on the geometry of the weld (e.g., double V, K-type, narrow gap, etc.) and the combination and setting of transducers.

Flaw Signal Levels

The quality of ultrasonic signals is most important for an automated system. Since the operator is removed from the interim decision making process, the setting of the parameters should be such that no room for ambiguity exists. This will assure that the threshold levels, setting of the angles of transducers and density of scanning will warrant the high defect detection probabilities.

Based on the limited experimental work the signal levels found on the test weld were:

- sufficient for the automated UT
- the required gain was $\sim$ 80 dB for unfocussed transducers and $\sim$ 60 dB for the focussed ones
- the signal to noise ratio was found to be consistently high. 10-20 dB for focussed transducers 6 - 10 dB for the unfocussed ones (see Figure 10).
- there was a substantial difference between the normal transducer and oblique transducer signal levels.

The difference in the required gain values were $>$ 20 dB.

This indicates that some gain control may be necessary for the common receiver.

Conclusions

The survey of the literature and the limited experimental work carried out in the course of this project prove that the ultrasonic method is the appropriate inspection method for testing of thick wall pressure vessels.

The choice of vessel material, e.g., $2\frac{1}{2}$ Cr 1 Mo steel presents no problem for the propagation of ultrasonic beams.

A multitransducer computer-controlled ultrasonic system is proposed to achieve the levels of inspectability defined by applicable ASME code and more. A special transducer, immersion coupled and focussed with long focal length, was chosen to inspect the root region of the weld. (This type of transducer is also advantageous for the inspection of stainless steel cladding, ref. 2). Simpler transducers can be used for other regions of the weld.

All the test defects were revealed with the above transducer, with sufficient resolution, and displayed in analog form of a modified C-scan.

For the proposed system the Z-80 based microcomputer will provide the scanning control and data acquisition functions. The simple printer-plotter routine is suggested for data display.

The system will also be adjustable for different weld geometries. As such, the system will be a cost effective answer to radiography or manual UT scanning.

Acknowledgements

The author wishes to thank the staff of Physical Metallurgy Research Laboratories, CANMET, Dr. J.T. McGrath and J. Gordine in particular for their interest in the project and numerous helpful suggestions. Special thanks are also due to J.M. Irvine and J.C. Pimentel for carrying out some experimental work.

References

1. Macecek, M. - "Nondestructive Evaluation of Heavy Section Pressure Vessels - Part I - State-of-the-Art Survey." WIC Report 1980.

2. Saglio, R., et al, - "Determination of Defect Characteristics Using Focussed Probes", Materials Evaluation, January 1978.

/ssm

TABLE 1

Coverage of the Weld by UT Beams

Transducer No.	Angle α	Entry Point (mm) from weld axis	Longest Path mm	Travel Time (μ sec)		Defect Type
				Long.	Shear	
1	70°	450.20	445.61	76.17	137.96	Lack of side wall fusion & cracking
2	60°	295.52	304.80	52.10	94.37	
3	45°	183.96	215.56	36.85	66.74	
4	70°	209.36	222.81	38.09	68.98	Lack of root pene ation. Lack of si wall fusion-crack
5	60°	131.98	152.40	26.05	47.18	
6	45°	76.23	107.76	18.42	33.36	
7	0°	-	152.40	26.05	47.18	Lack of interpass fusion

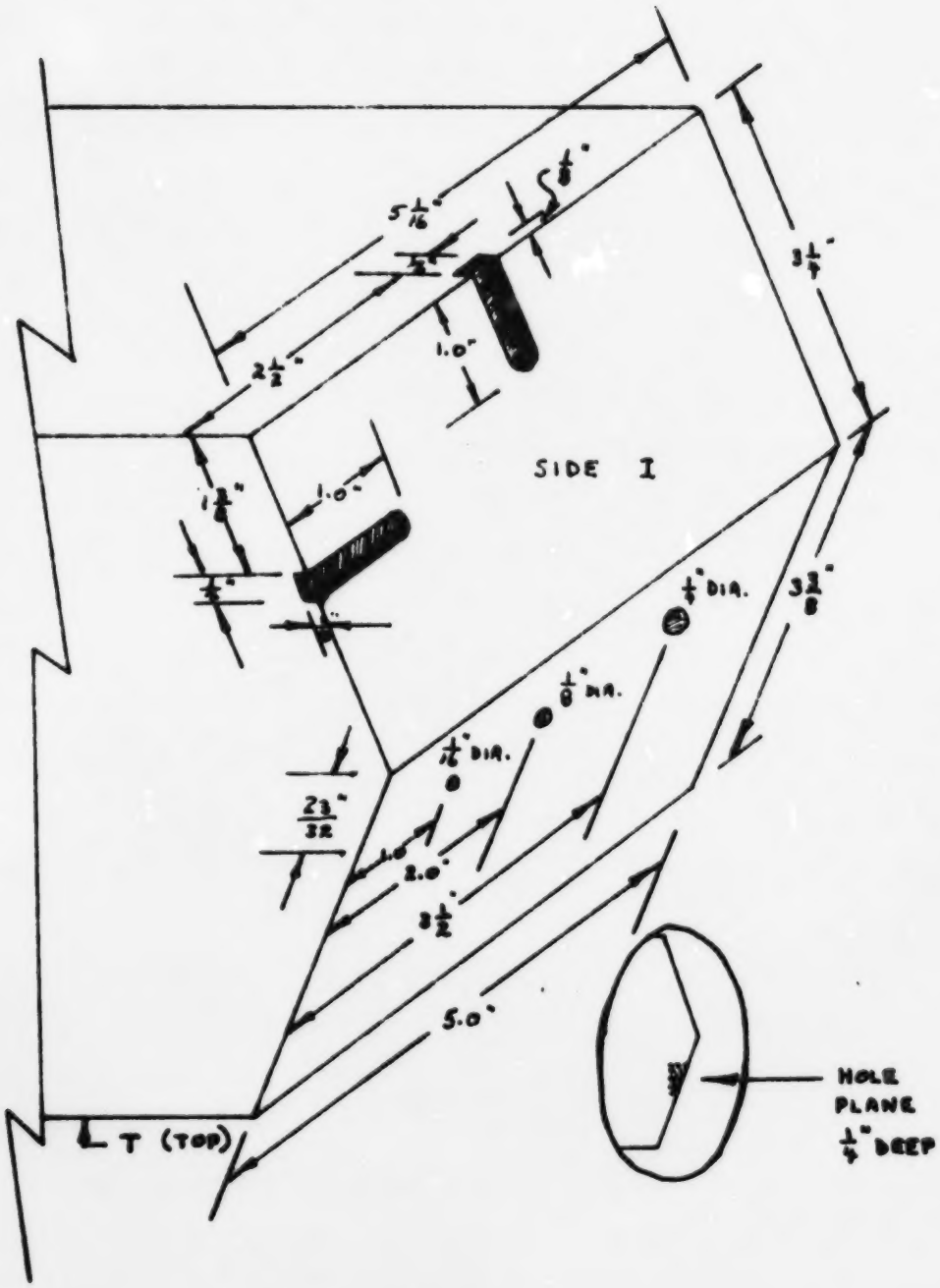

Figure 1 : Introduction of Artificial Defects
Prior to Welding

Figure 2 : Macrosection of the Welded Sample Showing the Number of Passes and the Weld Geometry

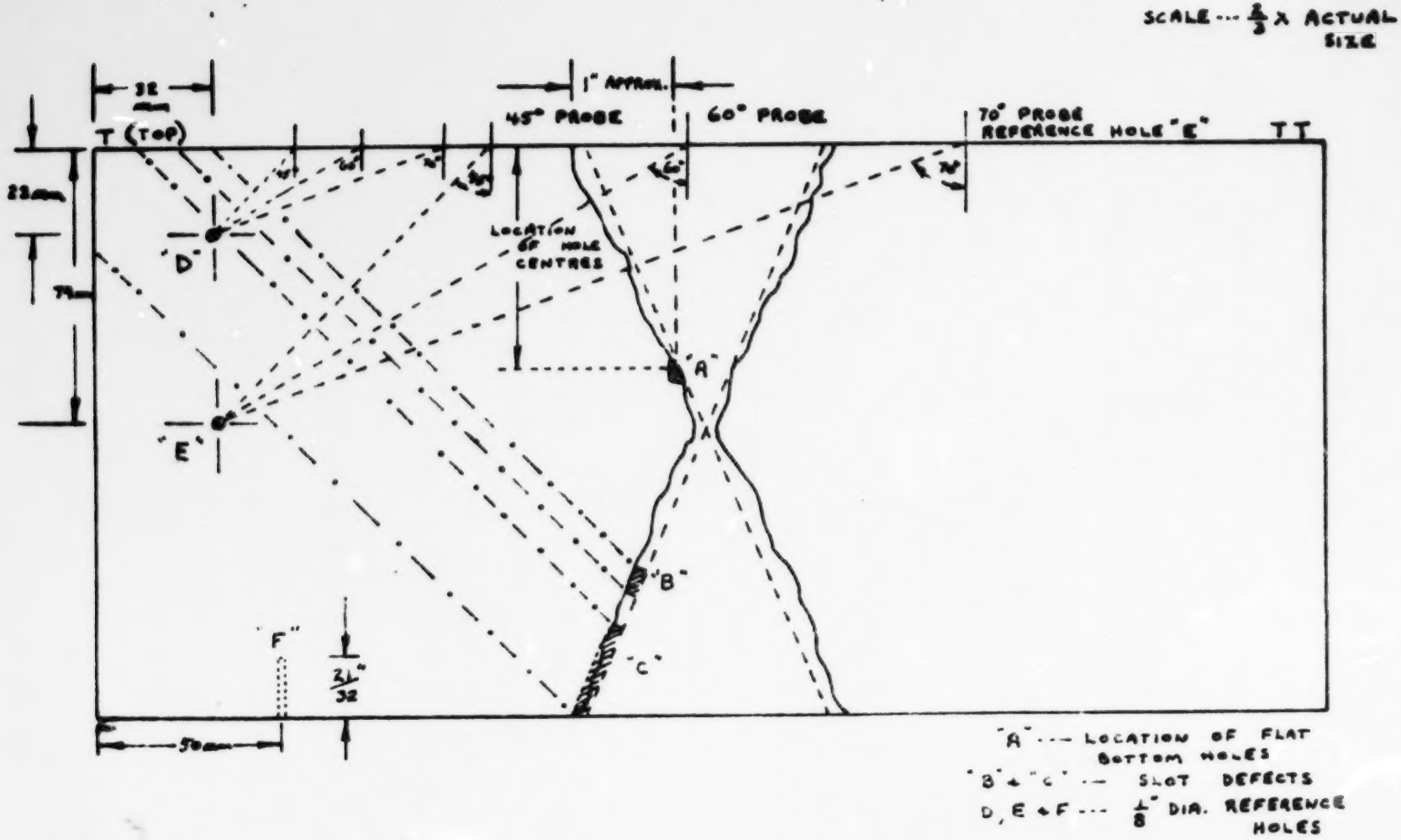

Figure 3 : Position of Side Drilled Reference Holes in the Weld Sample

Figure 4 : Overall View of the Prepared Thick Wall Sample

Figure 5: Print of γ radiography of the test weld showing only the 0.25" (6.25 mm) side drilled hole

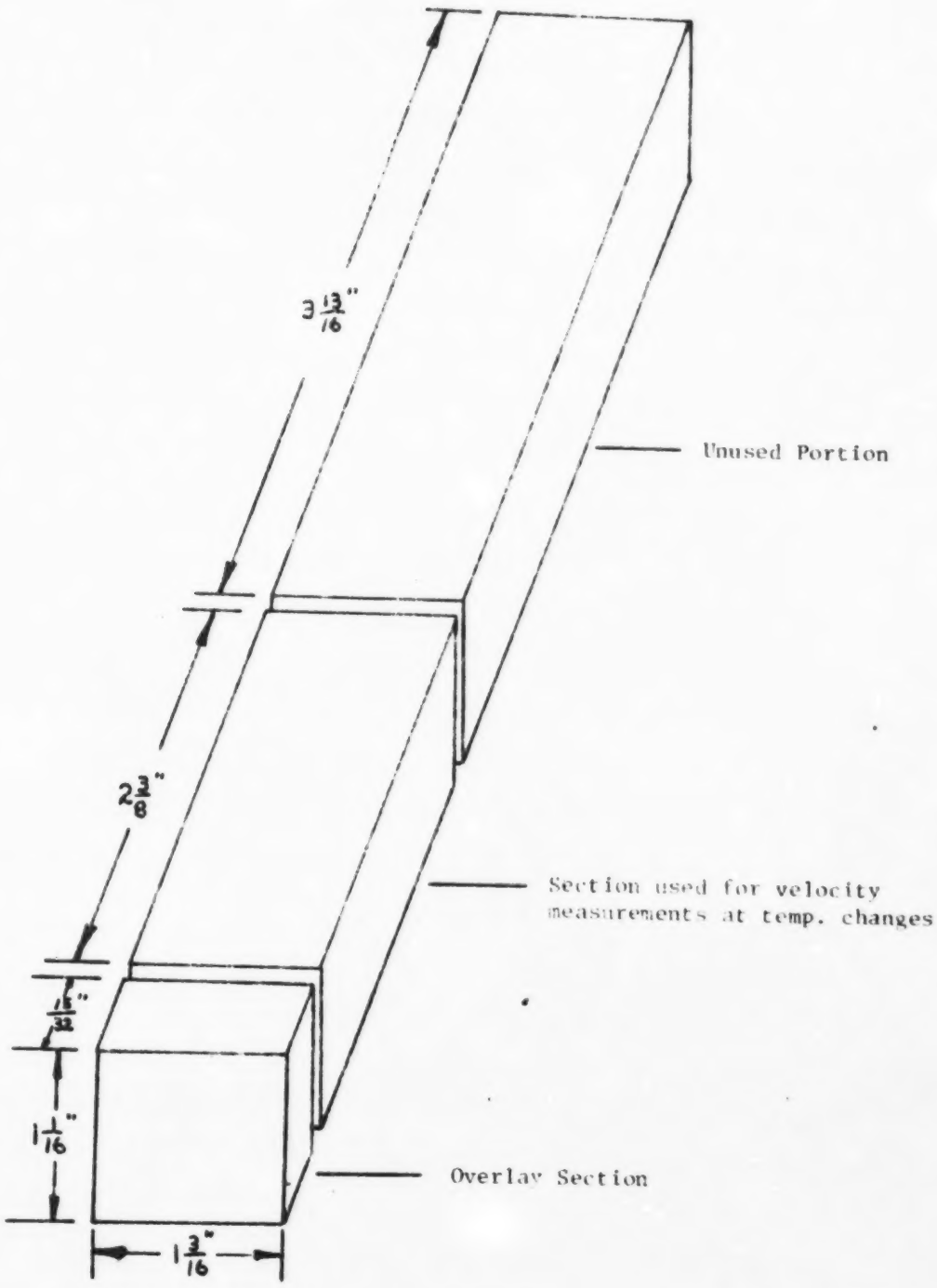

Figure 6 : Geometry of the Pressure Vessel Steel Sample used for the UT Velocity Measurements

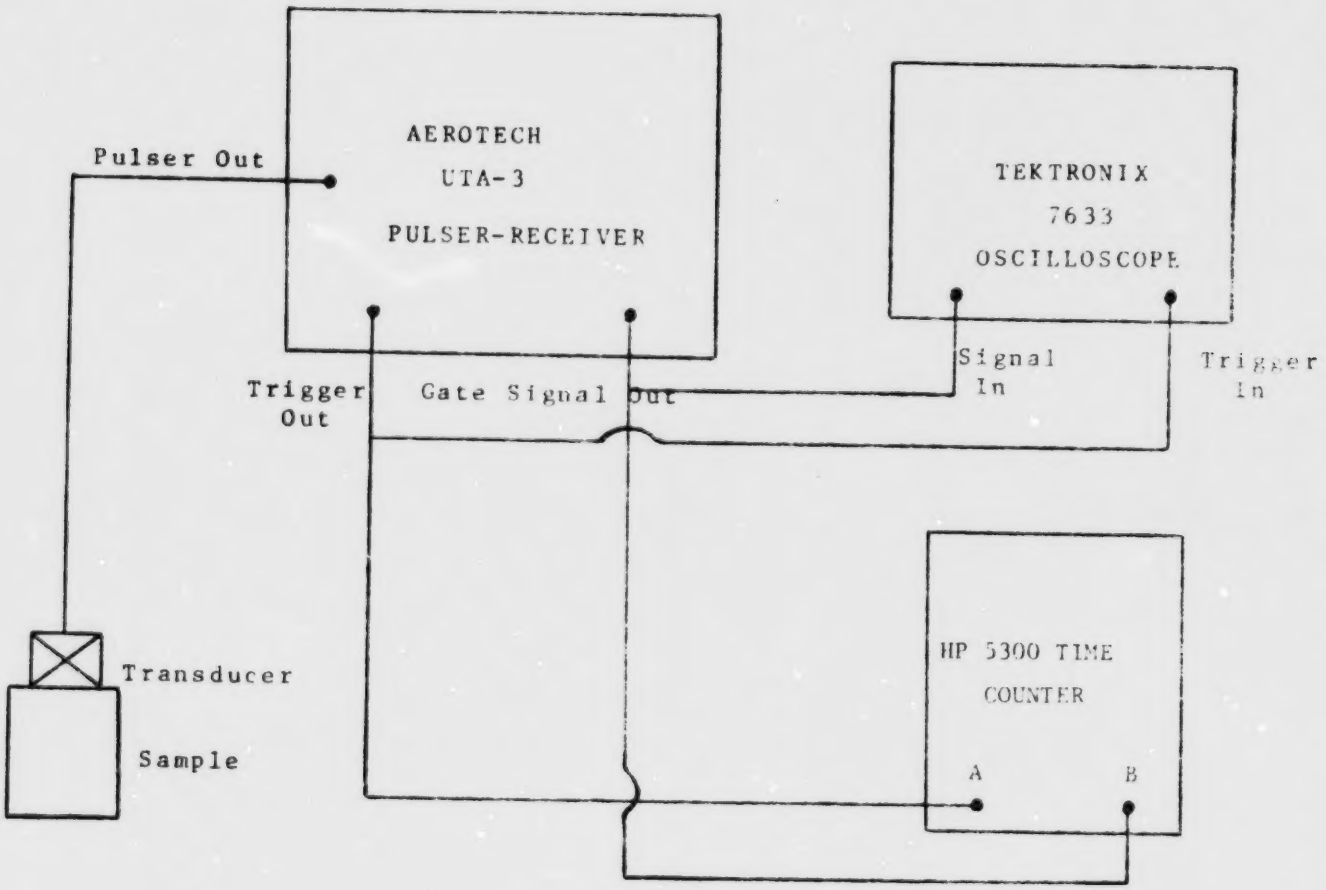

Figure 7: Block Diagram of the Set-Up for Velocity Measurements

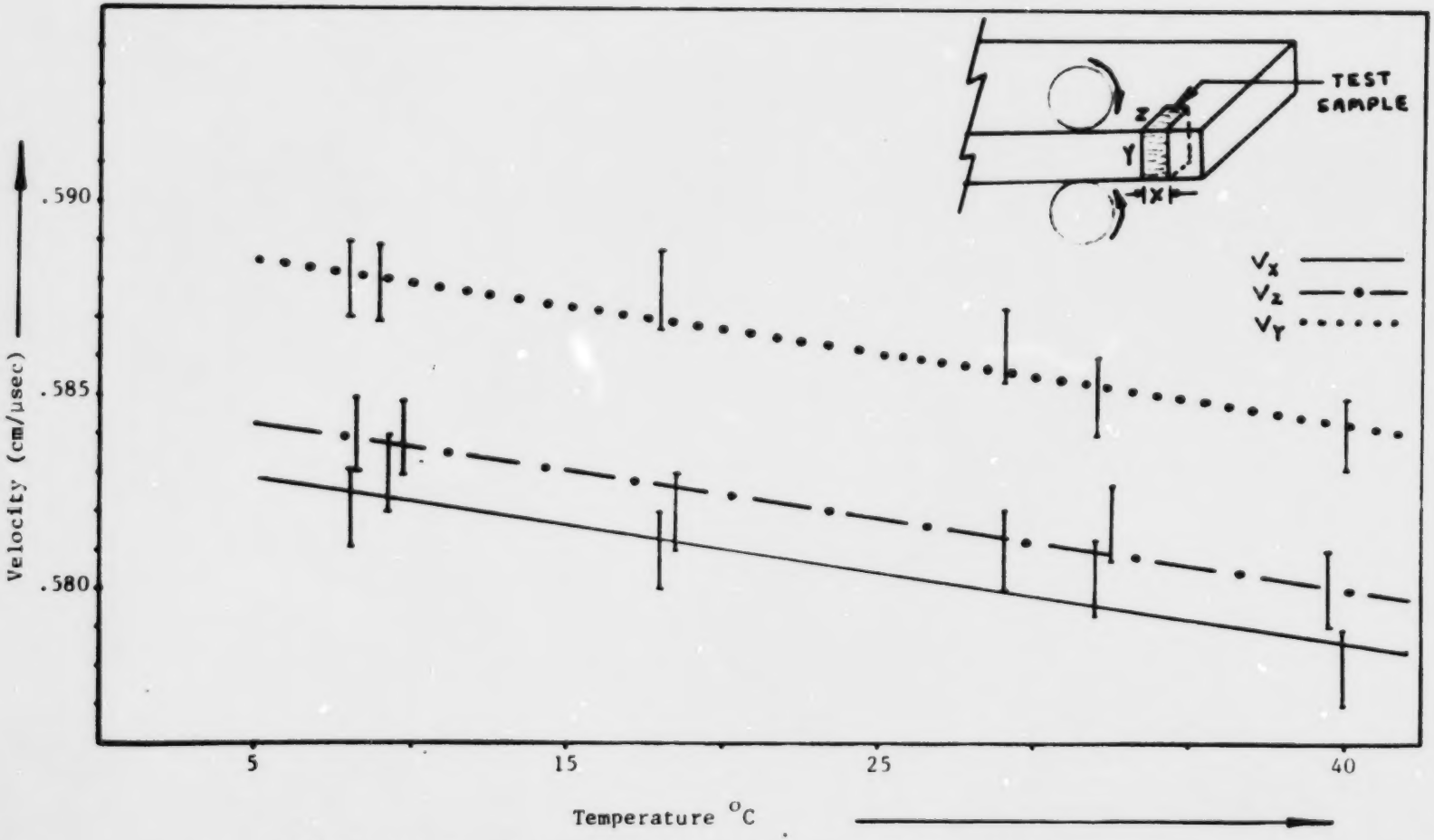

Figure 8 : Temperature Dependence of Ultrasonic Velocities in the Pressure Vessel Steel Plate

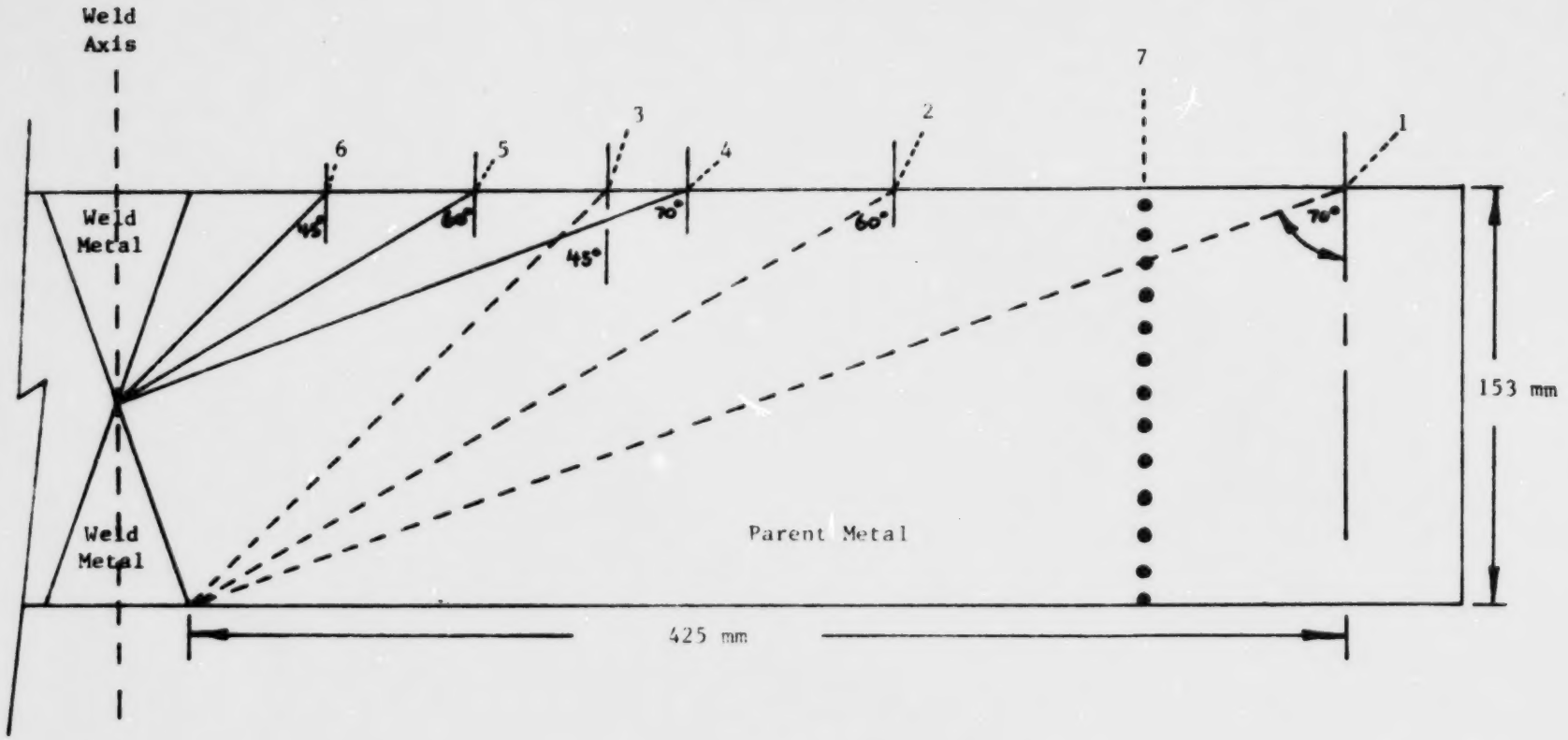

Figure 9 : Coverage of the Weld Region by Beams from Different Ultrasonic Transducers

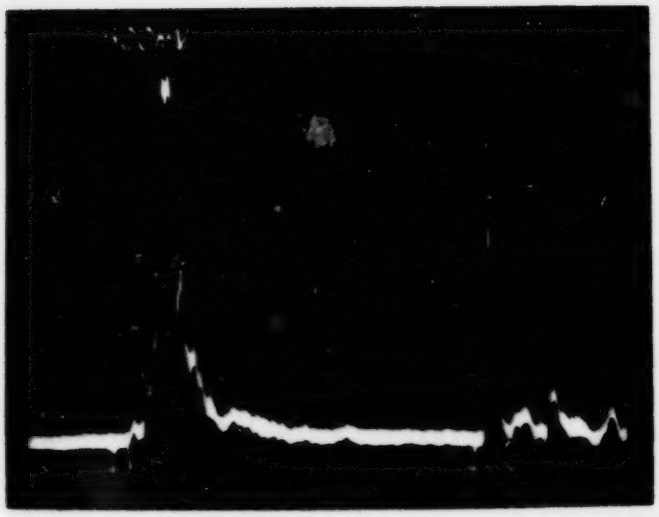

Figure 10: UT signals from the 1/8" FBH, 2.25 MHz, focussed transducer.

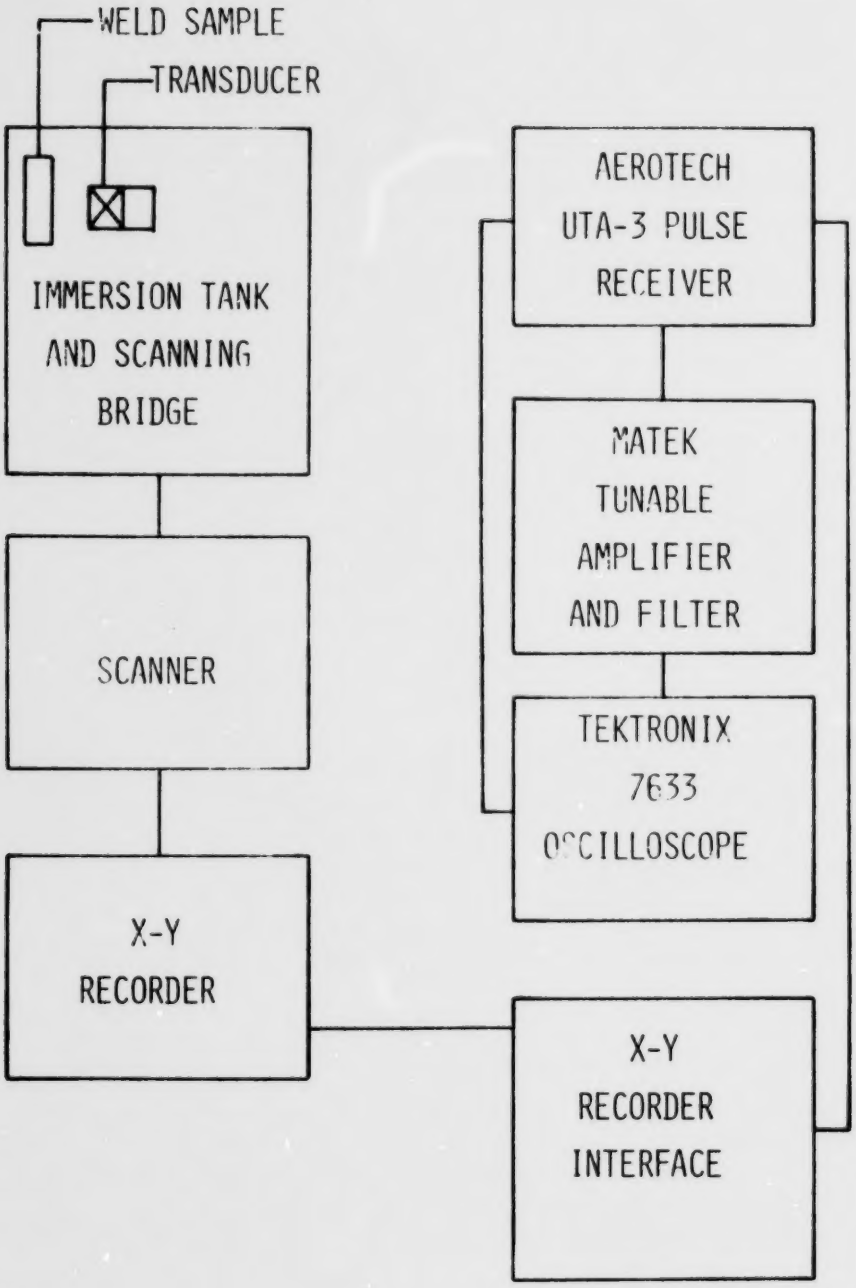

FIGURE 11 : BLOCK DIAGRAM OF THE ULTRASONIC SET-UP USED FOR THE IMMERSION SCANNING OF THE THICK WELDMENT

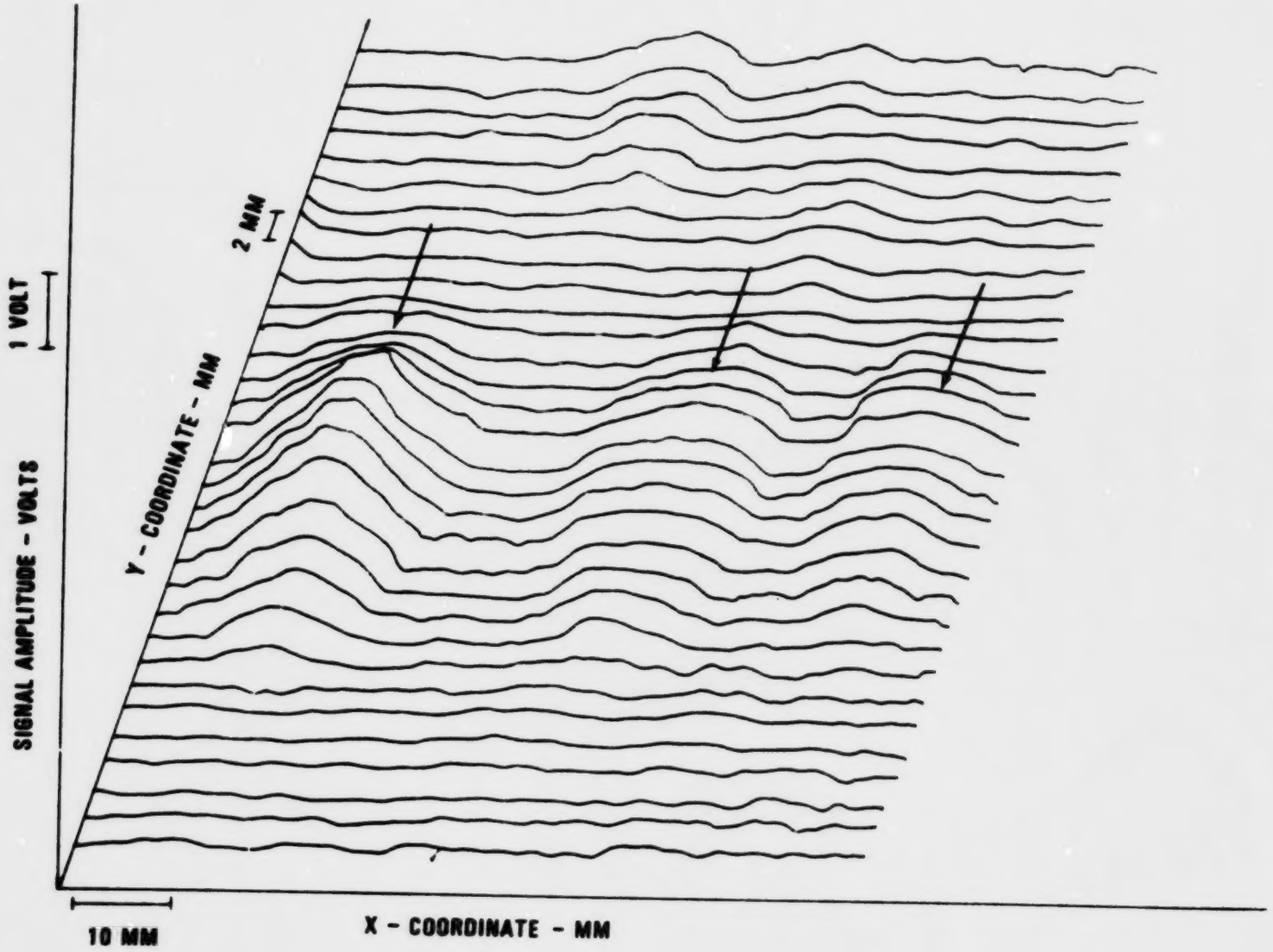

Figure 12: Modified c-scan of the weld showing all three holes (½", 1/8", 1/16") (2.25 MHz, 0.5" dia., immersion transducer)

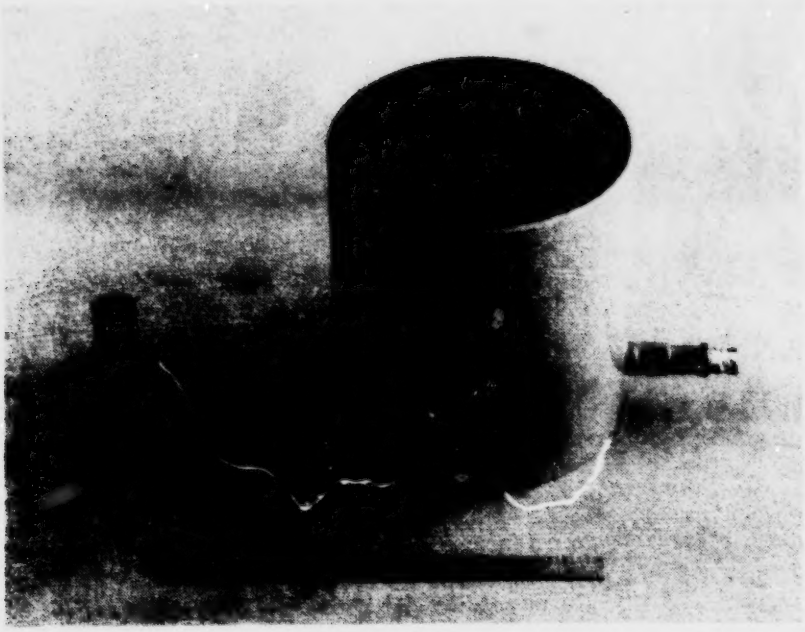

Figure 13 : Comparison of a Standard and a Large Diameter Focussed Transducer

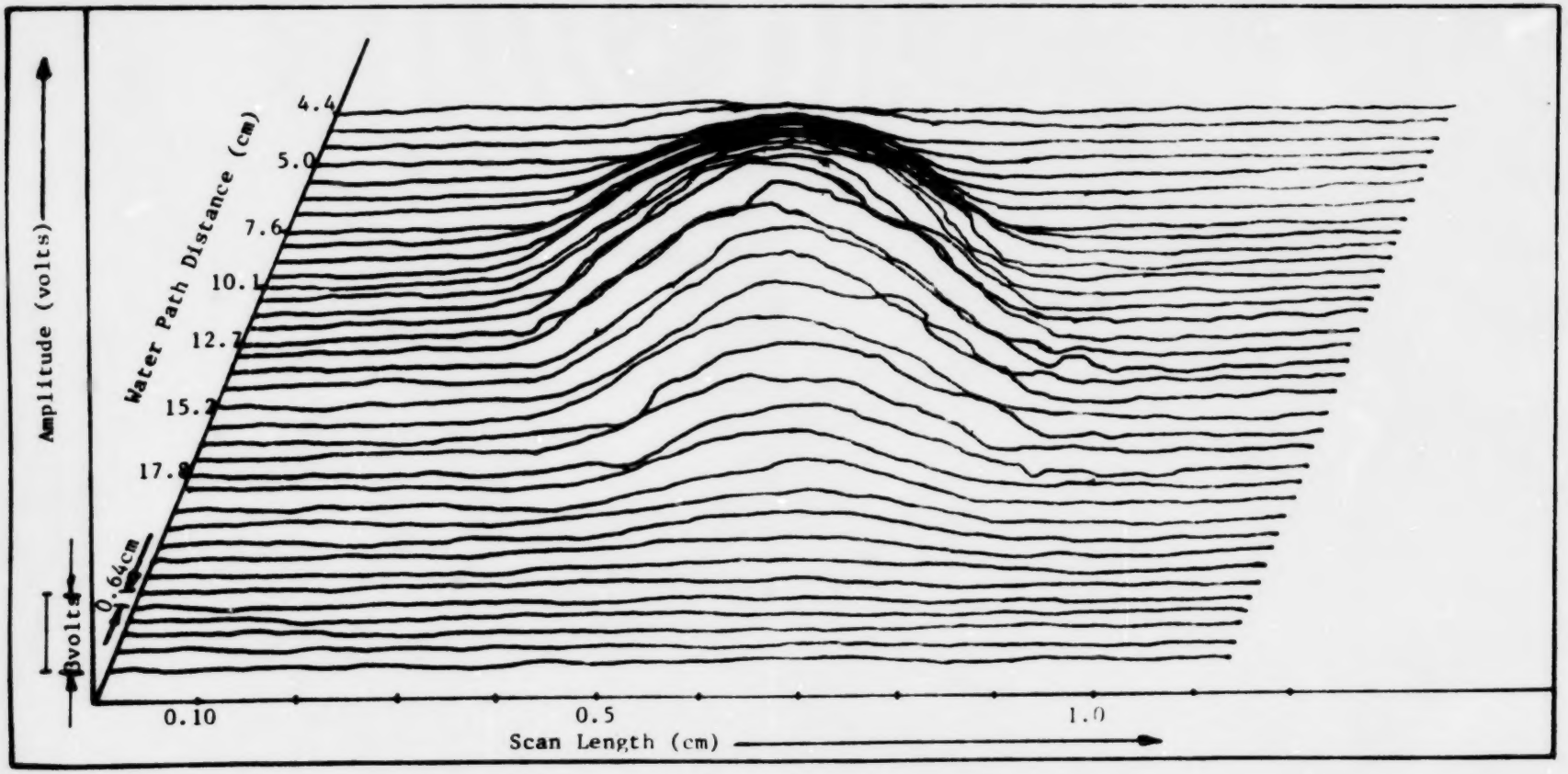

Figure 14 : Modified C-Scan Using the 4" Diameter Focussed Transducer (1/8" dia. FBH, 0.5" from the bottom of the plate).

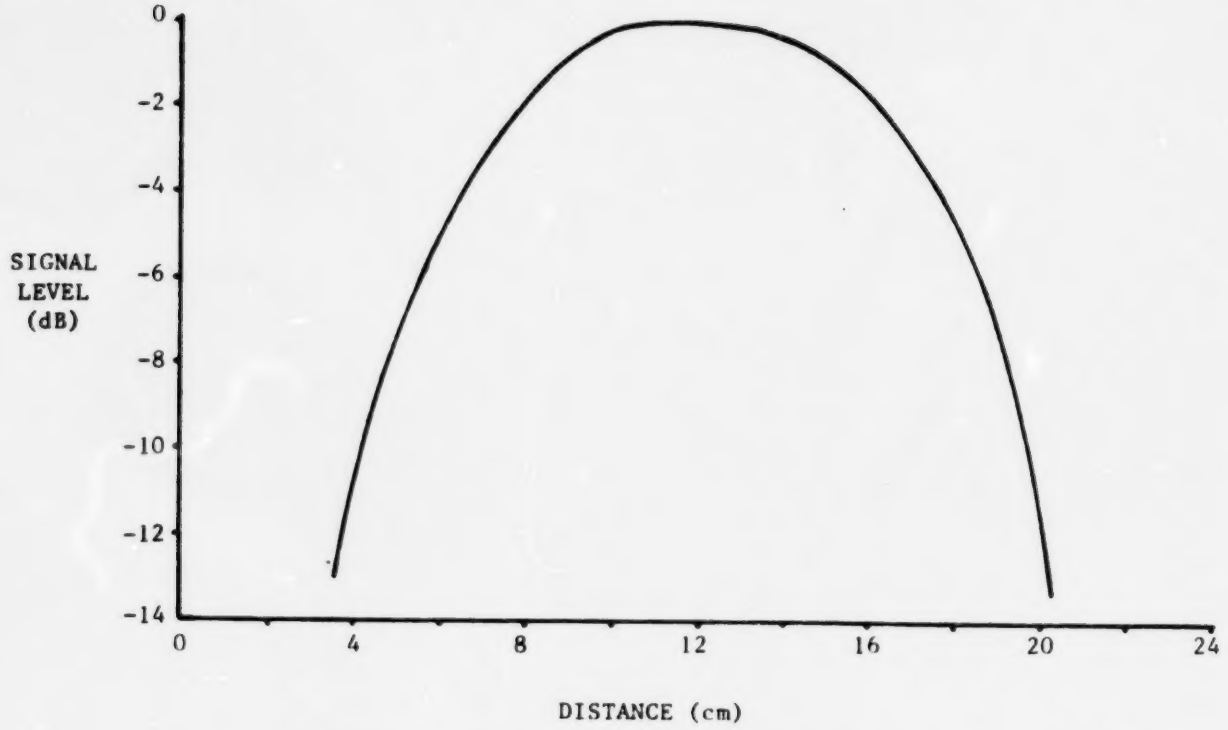

Figure 15 : Distance Dependence of the Signal Amplitude from a 1/8" Reflector taken from Figure 14 (the -6 dB region is 5" in water)

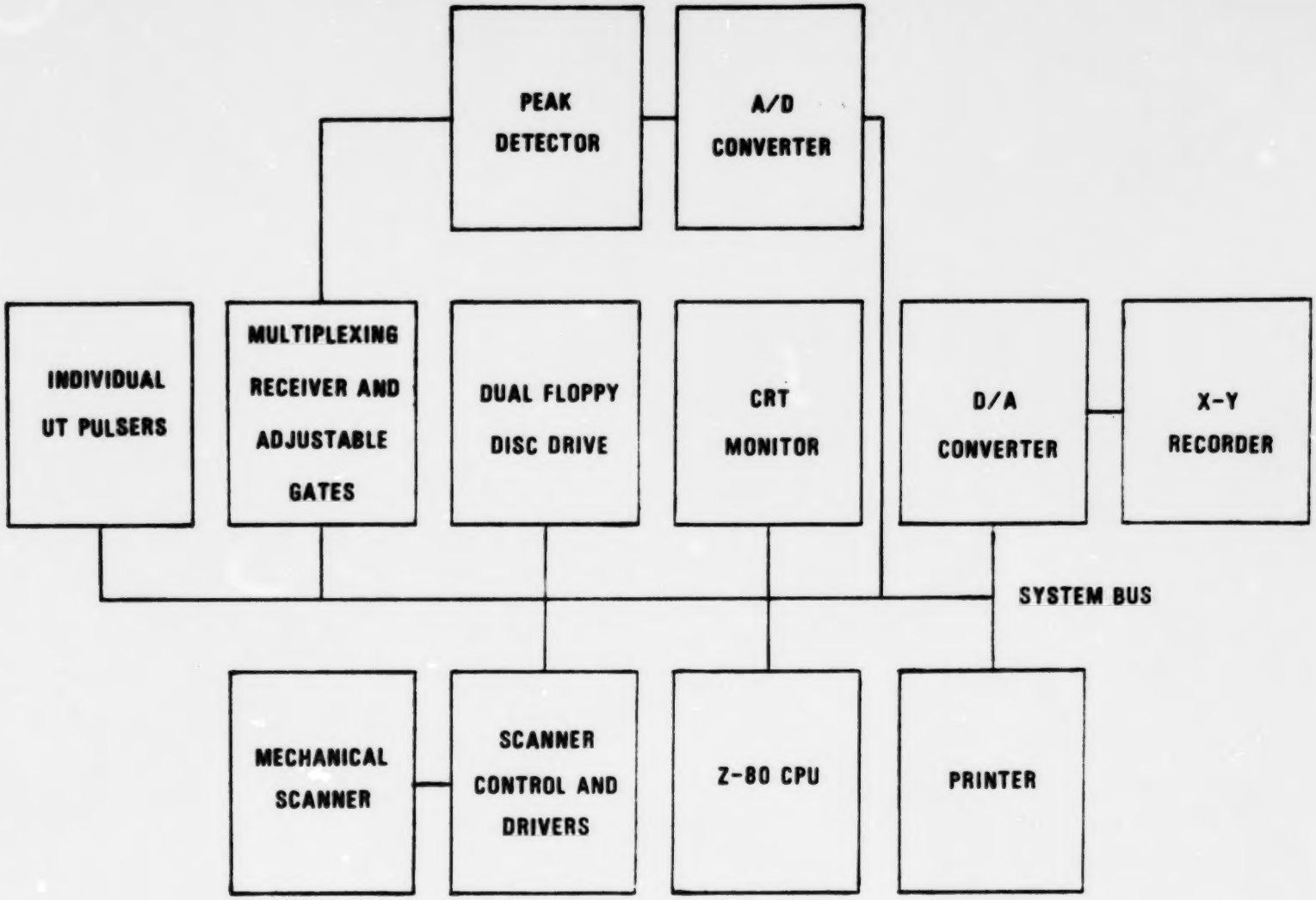

Figure 16: Proposed automated UT inspection system.